Sensitivity of the atmospheric response to sea-surface temperature forcing in the South West Indian Ocean: a regional climate modelling study

K. Hansingo* and C.J.C. Reason*†

The MM5 regional climate model has been used to investigate the sensitivity of the atmospheric response to sea-surface temperature (SST) forcing in the South West Indian Ocean. Two model runs were analysed and compared against each other; namely, one in which the model was forced by an observed warm SST anomaly during a summer season with above-average rainfall over southern Africa, and the other in which the model was forced with a smoothed representation of this anomaly but with the centre shifted closer to the east coast of South Africa. The latter experiment was motivated by correlation analyses between rainfall and SST and by previous experiments with coarser-resolution global circulation models, which suggest that the model response over the land is larger if the SST forcing is shifted closer to it. Analysis of the differences in the model response between the two runs suggests that, consistent with the global models, the MM5 response is indeed larger over southern Africa and more conducive to above-average rainfall in the experiment with the smoothed and westward shifted SST forcing. Increased evaporation over the South West Indian Ocean, local uplift and enhanced moisture flux westwards into southern Africa (as well as southwards over the land from the equatorial region) all play a role in enhancing the regional atmospheric conditions favourable for rainfall over a large area of southern Africa during the season simulated.

Introduction

The influence of sea-surface temperature (SST) variability in the South Indian Ocean on southern African austral summer rainfall has been investigated in recent decades using mainly observational and statistical analyses. Previous work (e.g. refs 1–6) has shown substantial relationships between rainfall and SST variability over various southern African regions and the South Indian Ocean (0–45°S). These studies provide strong evidence of inter-annual variability in SST in the South Indian Ocean and its link with observed rainfall variability over southern Africa. Positive SST anomalies in the South West Indian Ocean (east coast of southern Africa to about 70°E) are associated with above-average rainfall over the summer rainfall region of South Africa.[6,7] Correlation analyses and atmospheric general circulation model experiments[6] indicate that this association with increased rainfall over southeastern Africa may be stronger when the positive SST anomalies are located to the southwest of Madagascar.

A dipole-like pattern in SST anomalies in the subtropical South Indian Ocean, seasonally phase-locked to the austral summer, may also influence southern African rainfall.[8] Positive (negative) SST anomalies south of Madagascar (off the west coast of Australia) characterize the positive phase of the dipole event. This phase is associated with above-average summer rainfall over a region of southern Africa stretching south from Zambia towards the south coast of South Africa. The negative phase (SST anomalies in the opposite sense to the positive event) tends to be associated with below-average rainfall. Atmospheric general circulation model (AGCM) experiments (e.g. refs 9, 10) provide support for this statistical relationship but suggest that the increased rainfall over the subcontinent is further enhanced when the warm SST anomaly is closer to the subcontinent than originally proposed in Behera and Yamagata.[8] These authors derived their SST anomaly pattern on the basis of an empirical orthogonal function analysis and a composite of six events (in 1968, 1974, 1976, 1981, 1982, 1993). Examination of SST patterns for these individual years, together with more recent cases (1999, 2000), indicates that the exact location of the positive and negative SST anomalies shifts substantially with a number of cases (e.g. 1981, 1993, 2000) showing large warm anomalies nearer the east coast of South Africa. On the basis of this result, and previous correlation analyses between SST and rainfall,[1,6] the idealized experiment described below uses an SST anomaly centred near 40–45°E.

In the study reported here, a regional climate model rather than an AGCM was used to model the atmospheric response. AGCMs are typically too coarse in horizontal-grid resolution to represent the tight SST, topographic and vegetation gradients in the region and a higher resolution regional model offers one possibility to improve this inadequacy (statistical downscaling from the AGCM being another). We examined the 1980/81 SST event and the regional circulation anomalies that characterize it, since this event was one of the strongest cases in recent decades and produced the most coherent above-average rainfall response over southern Africa (Namibia being one of the few areas where near- or below-average rainfall occurred during this summer). The MM5 regional climate model (RCM) was used to analyse the difference in atmospheric response over southern Africa between the observed 1980/81 SST anomaly in the South West Indian Ocean (as derived from the NCEP Re-analysis dataset[11]) and an idealization of this forcing that represents a smoothed warm SST anomaly nearer the South African coast. By comparing the output of the two runs, some indication of the sensitivity of the model atmospheric response to a shifted and smoothed SST forcing may be obtained.

Model and data

The Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) fifth generation mesoscale model version 3 (MM5V3, hereafter referred to as MM5)[12] was used in our study. This is a high-resolution, terrain-following sigma-coordinate atmospheric model and is likely to represent SST gradients that are known to be significant for southern African weather and climate (e.g. refs 13, 14) better than an AGCM. The MM5 model is expected to capture features associated with the SST forcing that may be difficult to simulate in AGCMs. Six-hourly National Center for Environmental Prediction (NCEP) re-analyses[15] at 2.5° horizontal resolution were used for the initial and boundary conditions of the MM5 integrations.

The MM5 model domain used in this study covers the southern African region and neighbouring western South West Indian and South East Atlantic oceans (0–45°S, 5°W–75°E, Fig. 2). The eastern edge is far enough east of Madagascar for the topography of the island not to interfere with the lateral boundary conditions. Around the lateral boundaries of the domain, the model is

*Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7701, South Africa.

†Author for correspondence. E-mail: cjr@egs.uct.ac.za

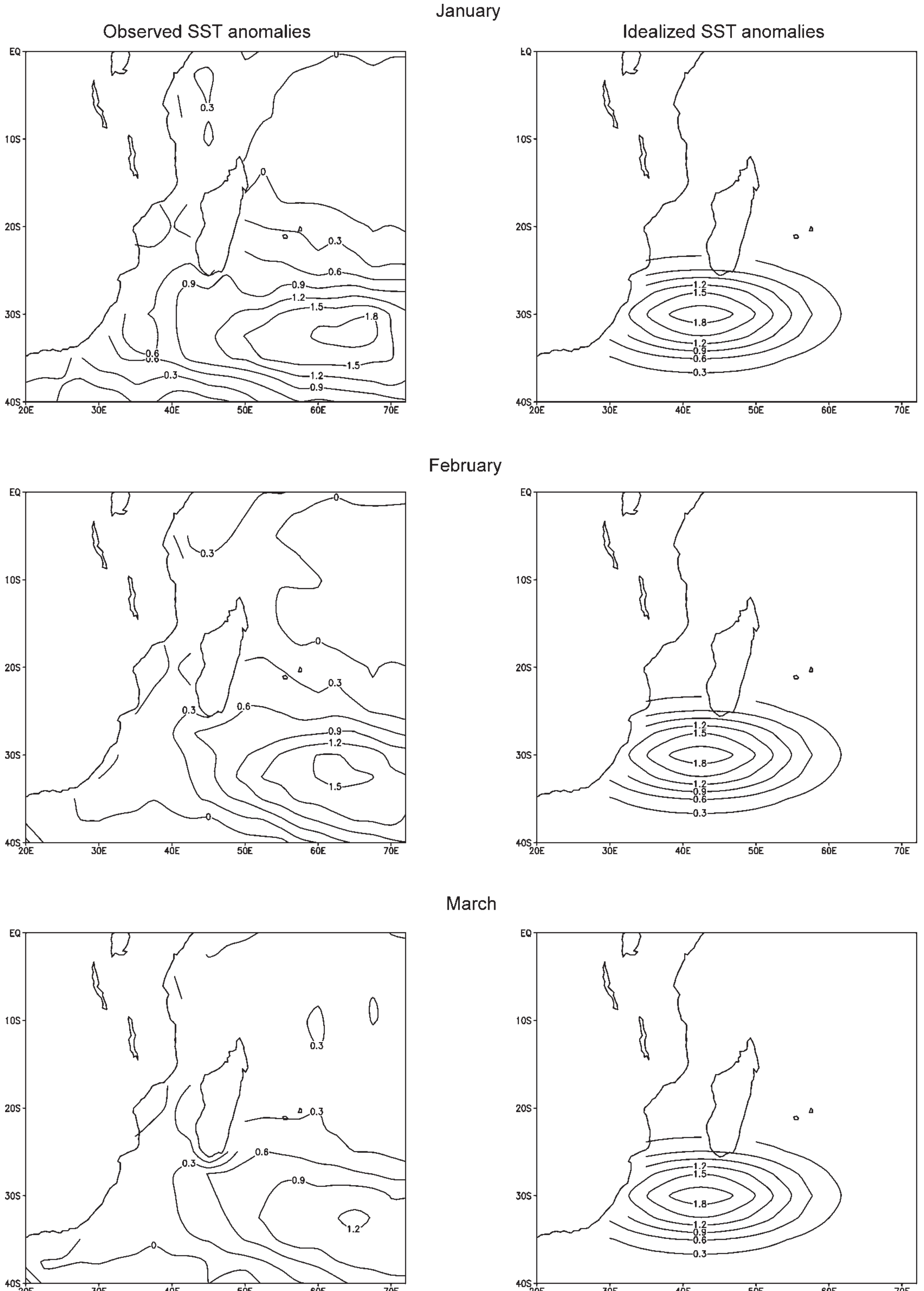

Fig. 1. The observed (left column) and idealized (right column) (contour interval 0.3°C in each case) SST anomaly pattern for January–March 1981 used to force the MM5 model.

nudged towards the NCEP re-analyses.[15] The latter were obtained by assimilating all available observations into the NCEP AGCM and therefore they contain the signature of SST forcing elsewhere in the Indian Ocean within them. A horizontal grid of 60 km × 60 km was used over the MM5 domain. Model runs were performed with a vertical grid containing 23 levels.

Three experiments, each having an ensemble of five different runs, and each initialized from a different time on November 30/ December 1 of the preceding year, were conducted. Each model run ended on 31 March. The month of December is regarded as the period of model spin-up to the imposed forcing and therefore plots for this month are not presented. In Experiment 1 (control), the model was forced with NCEP re-analyses daily skin temperature (SKT) climatological data derived from 30 years of NCEP data. Experiment 2 is a simulation of the 1980/1 SST event using the observed SST forcing[11] for this period. In Experiment 3, a smoothed representation of the 1980/81 SST anomaly was used in which, following Reason,[9,10] an elliptical

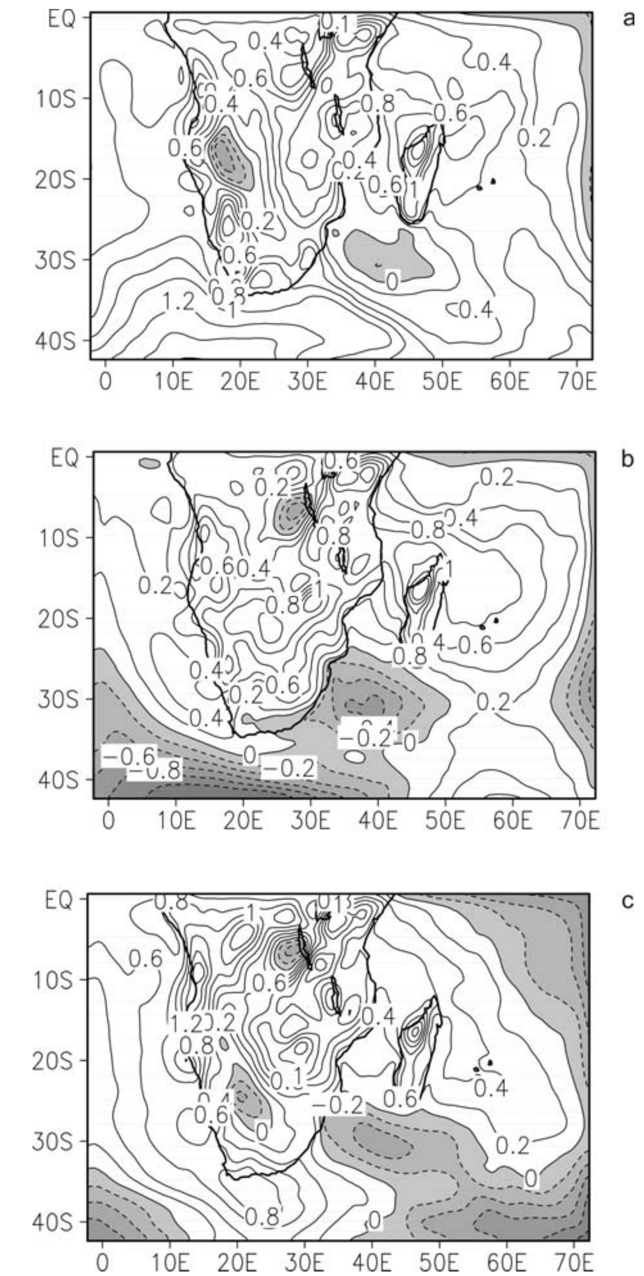

Fig. 2. Sea-level pressure differences between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. The contour interval is 0.2 hPa. Shading represents negative (cyclonic) differences.

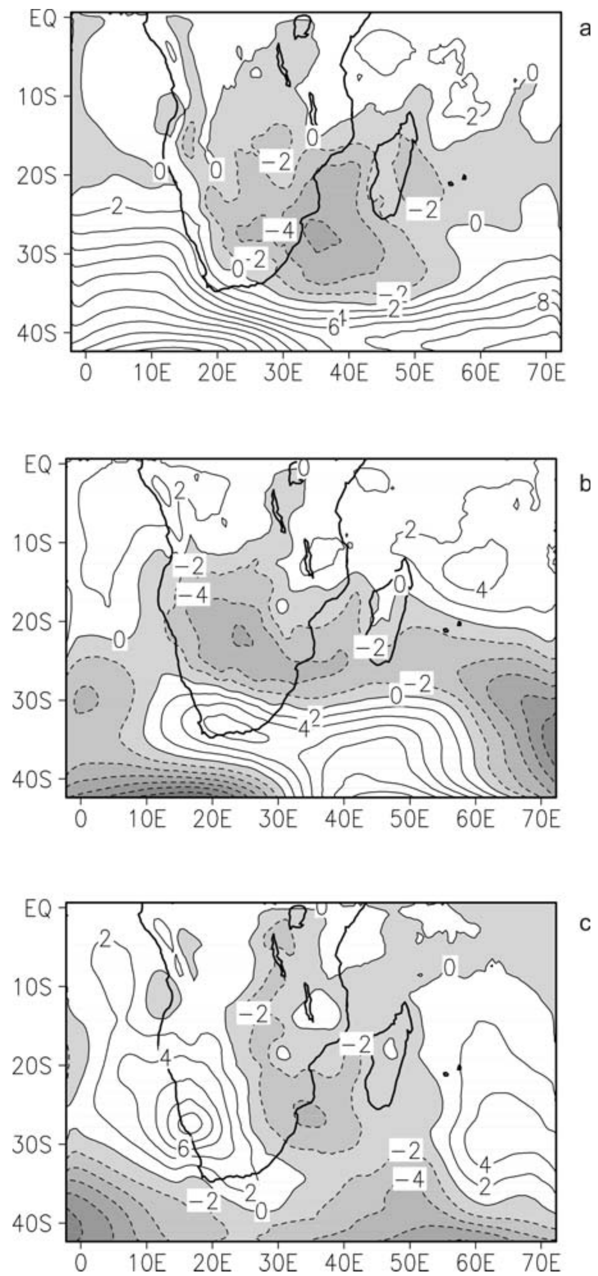

Fig. 3. 500-hPa geopotential height differences between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 2 m. Shading represents negative (cyclonic) differences.

positive pole anomaly, with +2°C in maximum magnitude and decreasing in size away from the centre, was imposed on the 30 years of NCEP re-analyses daily SKT climatology. This anomaly is located with centre near 40–45°E as motivated by the previous AGCM experiments[9,10] and correlation analyses.[1,6] The purpose of this experiment was, first, to assess the response of the model to a large-scale, coherent idealized SST anomaly which, we hope, would be easier to diagnose than for the observed SST forcing, and, second, to determine whether the MM5 response is more sensitive to a warm SST anomaly near the coast as was found in the AGCM experiments.

Figure 1 shows two SST anomaly patterns, the observed 1980/81 case (Experiment 2) (left) and the smoothed idealized version (Experiment 3) (right). These figures represent monthly differences from the climatological SST used in Experiment 1. Note that Experiment 3 effectively used a constant idealized SST anomaly imposed on climatology. However, in Experiment 2, the magnitude of the SST forcing weakened from January to March, although the location of the forcing was more or less the same as that in Experiment 3 with only a slight eastward shift from January to March. Figure 1 indicates that the magnitude of the observed SST anomaly (left-hand panels) weakened from about 1.8°C in January to about 1.5°C in February, and to about 1.2°C in March. The magnitude and centre of the idealized warm pole forcing (right-hand panels) was constant and located at 42°E, 30°S throughout the integration period. At this centre, the magnitude is 2.0°C but it decreased with distance from this point.

In the following sections, we discuss difference plots between Experiments 2 and 3. An analysis of Experiments 1 and 2 has already been performed,[16] in which the model response was shown to be consistent with observations. It should be noted that NCEP latent heat and moisture fluxes are less reliable than primary variables such as wind or geopotential height and caution therefore should be exercised when interpreting the results of these fields.[15]

Results

Sea-level pressure and geopotential height differences

We present results for the three months of January, February and March. Although the model was initialized on December 1 of a given year, we do not consider results for December, since we regard this as a period of adjustment to the forcing.

Linear quasi-geostrophic theory[17,18] suggests that a low pressure anomaly which decays with height is generated over and downstream of a warm SST anomaly. AGCM experiments with subtropical–mid-latitude SST anomalies tend to show a baroclinic response to surface heating, which is characterized by a low-level trough and an upper-level ridge.[6,19] Consistent with these results, a stronger low pressure is generated over the warm SST anomaly in the idealized SST experiment compared to the observed SST experiment (Fig. 2). Note that the plots in this case were obtained by subtracting the observed SST experiment results from those of the idealized experiment (i.e. Experiment 3 minus Experiment 2). The strength of the low surface pressure anomaly varied through the three months, consistent with the varying difference between the two SST anomaly patterns (Fig. 1). The mean sea-level pressure (MSLP) difference (Fig. 2) is larger in February and March when the difference in the maxima between the two SST forcings is greater than between January and February.

Inspection of the 500-hPa geopotential height differences (Fig. 3) shows that the low pressure anomalies decay with height in February and March, and that there is some downstream advection of the response by the mean flow to the west (east) in the subtropics (mid-latitudes). This advection by the mean flow is particularly strong in the last month of the experiment, March, and in the mid-latitudes, consistent with a robust cyclonic circulation anomaly induced by the forcing continually being swept downstream during the run by the mean mid-level westerly flow south of about 30°S. In all three months, the area of negative height differences extends substantially inland, suggesting more uplift and convective rainfall over southeastern Africa in the idealized SST experiment than in the observed one. These negative differences over the land strengthen in February but weaken just offshore. In March, the negative differences in 500-hPa height occur over the eastern half of the land, and strengthen substantially over the South West Indian Ocean in a distribution that encourages linkage between easterly disturbances over the land and mid-latitude depressions to the southeast. As a result, tropical temperate trough formation and good rains over southeastern Africa are more likely in the idealized SST than in the observed SST experiment.

Moisture flux and specific humidity

Wet summer seasons over southern Africa are characterized by large absolute values in specific humidity, which may be as a result of increased moisture flux over the subcontinent from the surrounding oceans. The tropical southeastern Atlantic Ocean is an important source of moisture for the western regions of southern Africa, particularly Angola and the Congo.[14] However, most of the moisture flux over southern Africa emanates from the South West Indian Ocean.[20–22] Figures 4 and 5 show moisture flux difference transects along 10°E and 40°E, respectively, for each month. At 10°E, or just upstream from the Atlantic coast of southern Africa, Fig. 4 suggests that there is increased low-level moisture transport from the South East Atlantic Ocean from the equator to about 13°S in the idealized SST experiment compared to the observed SST experiment. This enhanced moisture advection from the tropical South East Atlantic Ocean to the

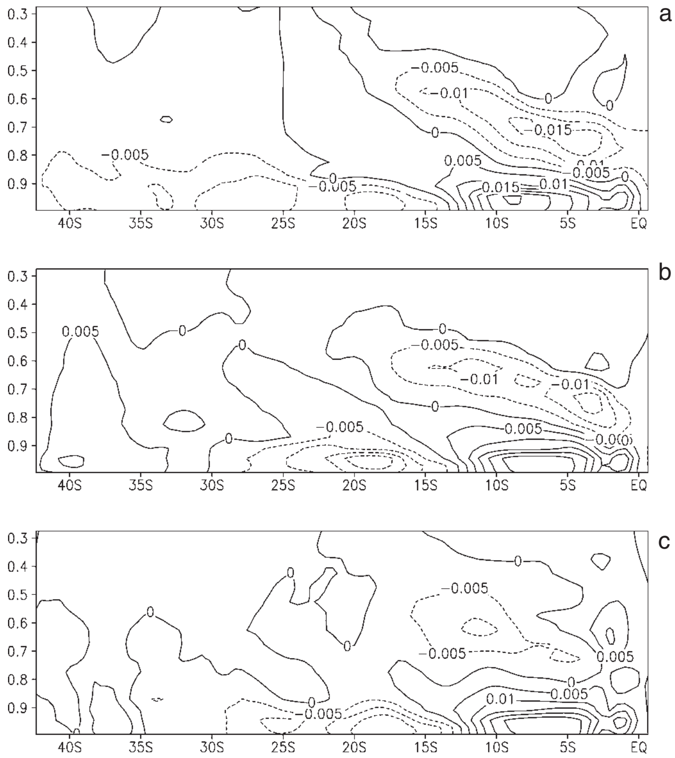

Fig. 4. Moisture flux differences through a transect along 10°E between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 0.005 g kg^{-1} m s^{-1} and positive values represent eastward transport towards southern Africa.

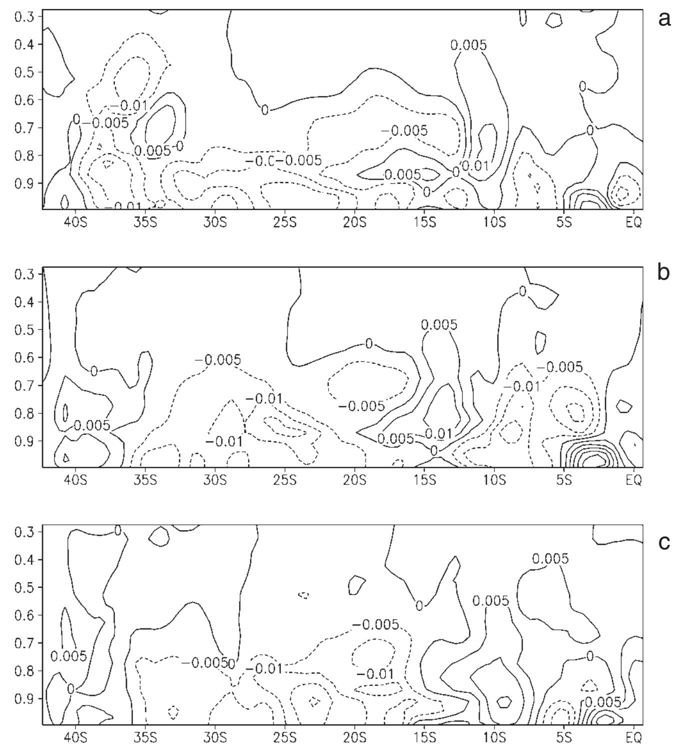

Fig. 5. Moisture flux differences through a transect along 40°E between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 0.005 g kg^{-1} m s^{-1} and negative values represent westward transport towards southern Africa.

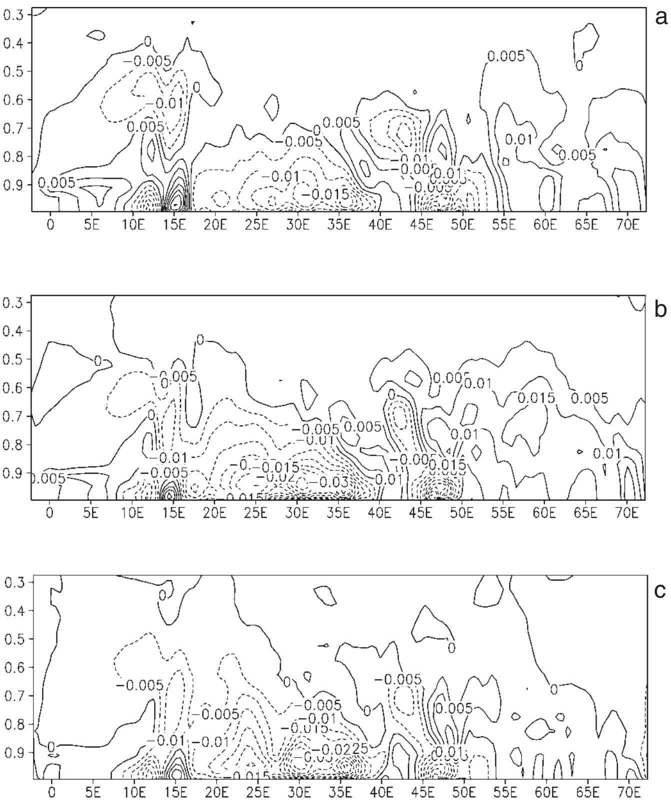

Fig. 6. Moisture flux differences through a transect along 15°S between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 0.005 g kg^{-1} m s^{-1} and negative values represent southwards transport towards South Africa.

western parts of the subcontinent is associated with the negative height differences over the subcontinent (Fig. 3), particularly in January and February, and to some extent with the strengthening of the Angola low in January (Fig. 2).

On the other hand, moisture flux transect differences along 40°E (near the Indian Ocean coast) for each month (Fig. 5) indicate increased easterly moisture advection into southern Africa south of about 15°S in the idealized SST experiment. This suggests that the central and southern regions of southern Africa receive more moist air from the South West Indian Ocean when the warm SST forcing is located just south of Madagascar as opposed to further offshore in the observed SST experiment.

To examine the strength of the moisture transport over the continent, transects of meridional moisture flux differences along a latitude of 15°S were derived (Fig. 6). These differences indicate a strong northerly moisture flux from the equatorial region southwards over southern Africa in the idealized SST experiment compared to the observed SST experiment in each month. Increased northerly fluxes are often associated with above-average rainfall[22] and hence Fig. 6 suggests that favourable rainfall conditions are more likely in the idealized SST experiment than the observed case.

Having discussed moisture fluxes, we now examine how much more moisture is available over the subcontinent in the idealized experiment compared to the observed one. Figure 7 shows 850-hPa specific humidity differences between the idealized and observed SST experiments for each month. Generally, there is more moisture in the former than in the observed SST experiment over the equatorial and eastern regions of the subcontinent. The increased humidity over the Congo basin (Fig. 7) may then feed into the northerly flux difference seen

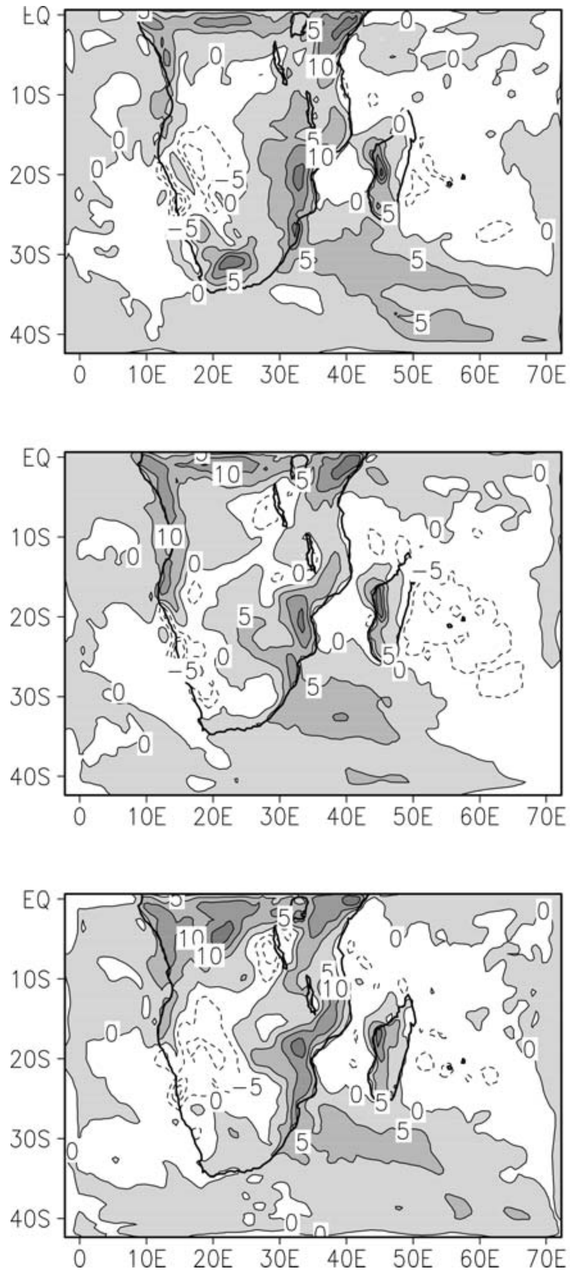

Fig. 7. Differences in specific humidity differences at 850 hPa between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 5 g kg^{-1} and shading represents positive differences or increased moisture.

in Fig. 6 and hence contribute towards enhancing convective rainfall over tropical southern Africa.

Latent heat flux, vertical velocity and outgoing long-wave radiation

Increased latent heat flux loss from the surface (Fig. 8) is observed over the surrounding ocean, particular over the region of the idealized SST anomaly. Areas of increased evaporation also occur in the tropical South East Atlantic Ocean in the idealized SST experiment and this contributes to the northwesterly moisture input into the confluence region between the ITCZ and the Angola low over central tropical southern Africa.[14,22] However, there is reduced latent heat loss over the subcontinent in the idealized experiment, suggesting that these ocean areas are the main sources of moisture rather than the land surface. An examination of differences in vertical velocity at 500 hPa (Fig. 9)

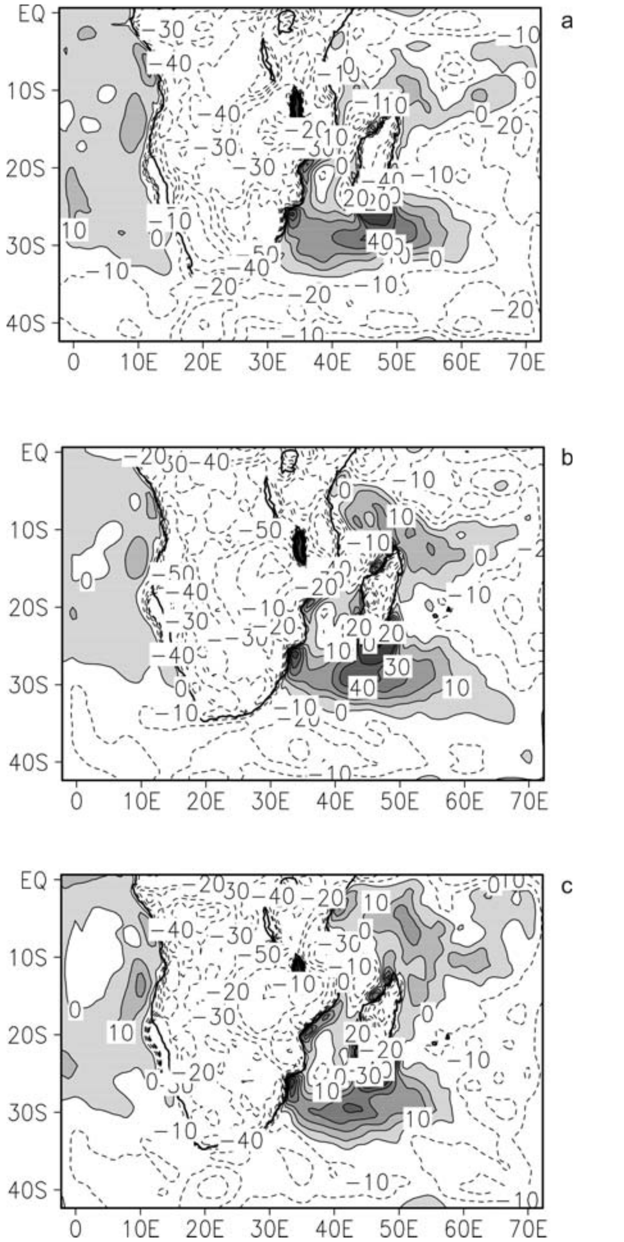

Fig. 8. Surface latent heat flux differences between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 10 W m^{-2} and shading represents positive differences or increased evaporation.

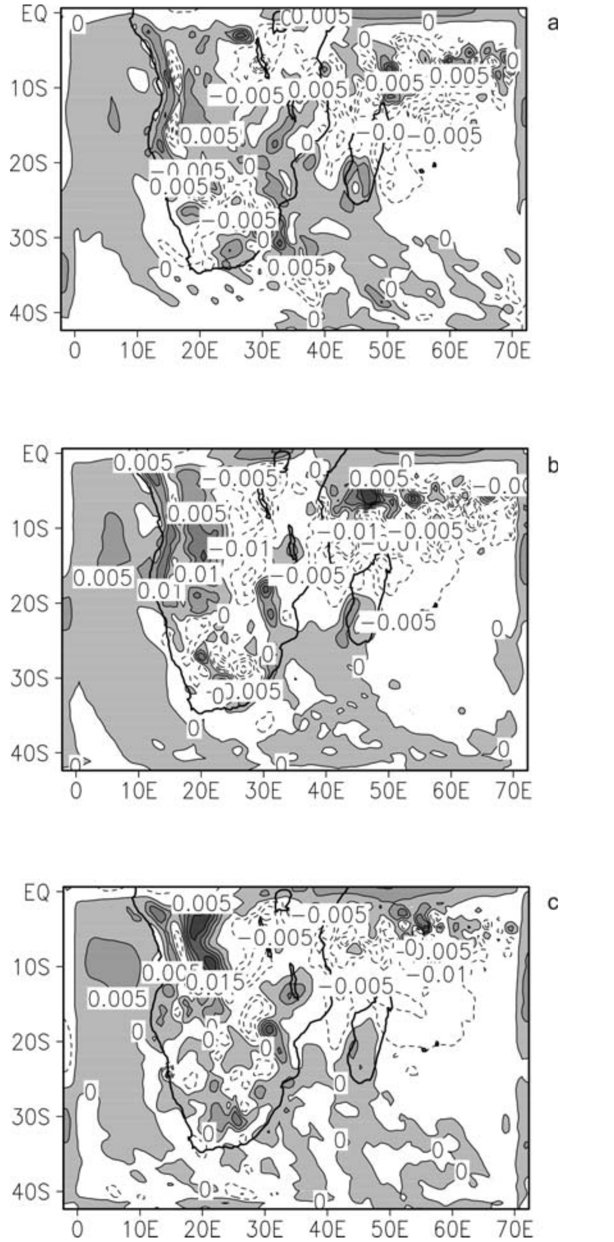

Fig. 9. Differences in vertical motion at 500 hPa between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 0.005 m s^{-1} and shading represents positive differences or increased uplift.

indicates increased ascent of moist air over most of the region of the SST forcing, the eastern landmass as well as the northwestern regions of the subcontinent. Positive differences in these regions indicate more uplift and hence suggest more favourable rainfall conditions in the idealized experiment than in the observed. Regions of negative differences in outgoing long-wave radiation (OLR) (Fig. 10) suggest increased convective cloud cover over large areas of southern Africa between the idealized and the observed SST experiments, particularly in the tropics and, except for February, most of South Africa. Strong negative differences are particularly seen over central southern Africa, implying increased convective cloud there.

Taken together, the geopotential height, humidity, moisture flux and OLR differences are consistent with enhanced convective rainfall over much of southern Africa, particularly the tropics and South Africa, in the idealized experiment compared to observations.

Discussion and conclusion

Experiments were conducted with the MM5 regional climate model to assess the sensitivity of the atmospheric response to SST forcing in the South West Indian Ocean. The experiments were motivated by previous observational[1,3,6] and global atmospheric modelling work[6,9,10] suggesting that regional atmospheric circulation and rainfall are sensitive to SST anomalies in this part of the ocean, particularly when these are close to the southern African landmass. The MM5 experiments confirmed the latter result and indicated that there are important changes to the main moisture flux pathways over southern Africa when the warm SST forcing is shifted closer to the land. These changes result to some extent from the cyclonic circulation anomalies generated over the region by the warm SST anomaly in the South West Indian Ocean. In addition, changes in vertical motion, surface latent heat flux, near-surface specific humidity and outgoing long-wave radiation (a proxy for convective rain-

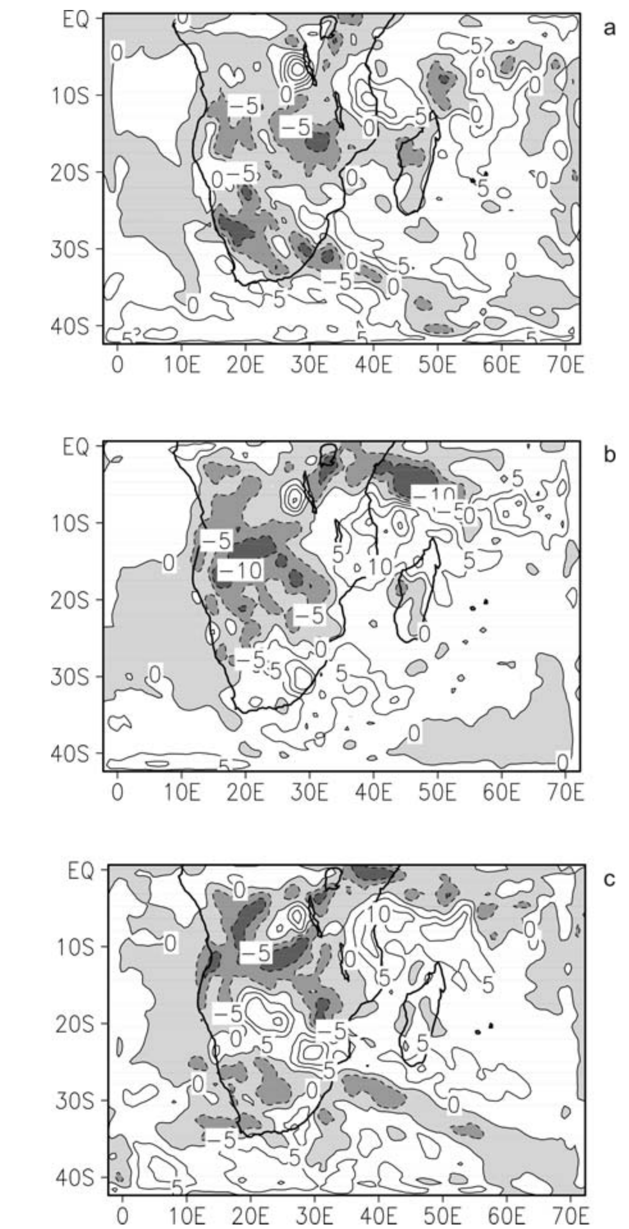

Fig. 10. Outgoing long-wave radiation differences between the idealized and observed SST anomaly experiments: **a**, January; **b**, February; **c**, March 1981. Contour interval is 5 W m^{-2} and shading represents negative differences or increased convective cloud.

fall) all support increased rainfall when the warm SST anomaly is close to land.

A potential criticism of the regional modelling approach is that it does not explicitly include SST anomalies elsewhere in the Indian Ocean in the domain. However, the signature of this SST forcing is included in the NCEP re-analyses for 1980/81 that provide the boundary conditions for the MM5 runs at the edges of the domain. We therefore consider that a domain that extends only as far east as 75°E is appropriate. A potentially more serious drawback is that the improved horizontal resolution of MM5 relative to that of a global model is still not sufficiently high to represent adequately the tight SST, topographic and vegetation gradients of the southern African region. Unfortunately, the only way to test this is to re-run the experiments at significantly higher resolution to determine if there is any obvious difference in the results. For example, it has been shown[23] that there are significant differences between NCEP surface heat fluxes off the core of the Agulhas Current and *in situ* measurements. It is likely that differences will also exist if the MM5 model was run for the same period as the week-long *in situ* measurements. However, on the month-to-season time scales of interest here, these differences are less likely to be of importance than for weather time scales.

Regional climate model experiments are expensive to run and the work presented here represents one of the few applications of these models in South Africa towards analysis of the climate variability of the subcontinent that exists at present. The results suggest that these models can be useful in process-orientated studies as an alternative to coarser-resolution AGCM investigations.

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